Response to Referee #1

General Comment

The manuscript addresses the record-breaking aerosol loading over the South China Sea (SCS) in April 2023, attributed to biomass burning (BB) over the northern Indochina Peninsula. While the topic is of regional and global importance, the study suffers from several critical issues. The methodology is overly simplistic, the novelty is limited, the logical flow is confusing, and key presentation elements (maps, data classification, figures) do not meet the standards of a top-tier journal. In its current form, the manuscript reads more like a descriptive case report rather than an in-depth scientific analysis. Substantial revision is needed before it can be considered for publication.

Reply: We thank the reviewer for the critical review of our original manuscript, which has helped us revise it for the better. Our point-by-point responses to the review comments are provided below. The authors sincerely thank the reviewer for dedicating the time and effort to evaluating our manuscript and for providing thoughtful, constructive feedback. We also appreciate the reviewer's recognition of the significance of our study. Their valuable comments have greatly contributed to enhancing the quality and clarity of our work.

All figures have been revised and improved in accordance with the reviewers' suggestions to enhance clarity and precision.

Major Comments

Scientific Significance and Novelty

Biomass burning over Indochina and its long-range transport to the SCS is a well-documented and recurring phenomenon (e.g., Lin et al., 2013; Reid et al., 2013). The manuscript merely shows that April 2023 recorded the highest anomalies in AOD/CO/ozone in the past two decades. Without deeper analysis of what makes 2023 fundamentally different (e.g., unique transport pathways, distinct chemical mechanisms, significant health/climate impacts), the work risks being a replication of prior studies with little added value. The authors need to explicitly demonstrate the **novelty** and scientific importance of this case beyond being "the largest on record."

Reply: The authors fully recognize the well-established link between biomass burning in Indochina (PSEA) and its transport to the South China Sea (SCS), Taiwan, and the western North Pacific, as shown in earlier research (Lin et al., 2013; Reid et al., 2013). The authors are well aware of the PSEA BB activity, its transport mechanisms, and its effects on regional weather and climate. However, the reviewer may have misunderstood the study's primary focus and its significant findings. While previous research indicates that most transported smoke stays north of about 17.5°N over the SCS, our analysis shows that **during April 2023, the smoke was unusually transported much farther south, reaching the southern parts of the SCS and even extending toward the southern Bay of Bengal (BoB).** This departure from typical patterns is significant. To illustrate this, we present the average April AOD distribution for 2003–2022 in Supplementary Figure 2 (now it is Figure 3 in the revised manuscript), which shows higher AOD levels across approximately 17.5°N-25°N, from northern Indochina to Taiwan. Conversely, the SCS region outlined in a black box generally exhibits very low AOD. The April 2023 event is notable for its intensity and spatial coverage. The AOD anomalies obtained are 4 times the long-term mean over most of the SCS and the southern BoB region in April 2023. We believe our study highlights a rare, previously unreported transport event, not simply reproducing prior work, with potential consequences for regional air quality and climate. We will emphasize this aspect further in the revised manuscript to clearly showcase the novelty and importance of the April 2023 case.

Mismatch Between Analysis and Conclusions

The conclusions claim clear attribution to Laos fires and anomalous circulation systems. However, the analysis is largely descriptive, relying on anomaly maps and percentage changes. The causal chain (fire activity → transport anomalies → AOD/CO increases → ozone formation) is not rigorously substantiated. For example, CO–AOD correlation (~0.65) only suggests coincidence, not causality. Ozone enhancement is attributed to BB emissions without distinguishing between primary transport and secondary chemistry. The authors should either strengthen the causal evidence (e.g., trajectory modeling, chemical transport simulations, Rossby wave diagnostics) or tone down the conclusions.

For example, CO–AOD correlation (~0.65) only suggests coincidence, not causality.

Reply: We appreciate the reviewer's valuable comments. In the revised manuscript, we have strengthened the analysis by incorporating HYSPLIT back-trajectory analysis, vertical aerosol profiles from CALIPSO images, and vertical changes of black carbon (BC) and organic carbon (OC) from MERRA-2 reanalysis. In addition, we have included an analysis of formic acid (HCOOH) to better illustrate the role of secondary photochemical processes in ozone formation over the South China Sea (SCS). These additions have been reflected in revised conclusions, with careful consideration of the evidentiary limits of the present study.

Regarding the CO–AOD relationship, we note that the manuscript mistakenly reported a correlation coefficient of 0.65; this is in fact the coefficient of determination (R^2). The corresponding correlation coefficient is R = 0.81, indicating a statistically robust association between CO and AOD over the SCS. While we agree that correlation alone does not prove causality, the strong CO–AOD relationship in this remote, marine region, largely free of local anthropogenic sources, supports the interpretation of long-range transport of combustion-related aerosols. Elevated CO, a tracer of incomplete combustion, observed far from urban and industrial sources, is consistent with biomass burning (BB) influence. Seasonal consistency further supports this interpretation: annual AOD maxima over Peninsular Southeast Asia (PSEA) in March–April and over the Maritime Continent in September coincide with their respective peak fire seasons. To strengthen source attribution, we analyzed daily HYSPLIT back trajectories, which show that air masses arriving over the SCS during April 2023 predominantly originated from northern PSEA, consistent with active BB regions during this period (Figure R1). While this trajectory analysis does not constitute a complete transport attribution framework, it provides dynamical support for BB influence.

We agree with the reviewer that ozone enhancement should not be attributed solely to BB emissions without distinguishing between primary transport and secondary photochemical production. In the revised manuscript, we explicitly clarify this distinction. Ozone anomalies over the SCS coincide with elevated CO and AOD; however, quantifying ozone production would require chemical transport modeling, which is beyond the scope of this study. Nevertheless, additional observational evidence supports secondary chemical processing within transported BB plumes. Infrared Atmospheric Sounding Interferometer (IASI) MetOp satellite observations show a ~100% enhancement in formic acid (HCOOH) over the SCS in April 2023 (Figure R2). HCOOH is a well-established secondary oxidation product of VOCs emitted by biomass burning. The simultaneous enhancements of CO (>50 ppb), AOD (~150%), and HCOOH indicate that BB plumes underwent substantial photochemical aging during transport. Therefore, the observed ozone enhancement is interpreted as primarily influenced by secondary ozone formation within transported BB plumes, rather than by direct ozone transport alone.

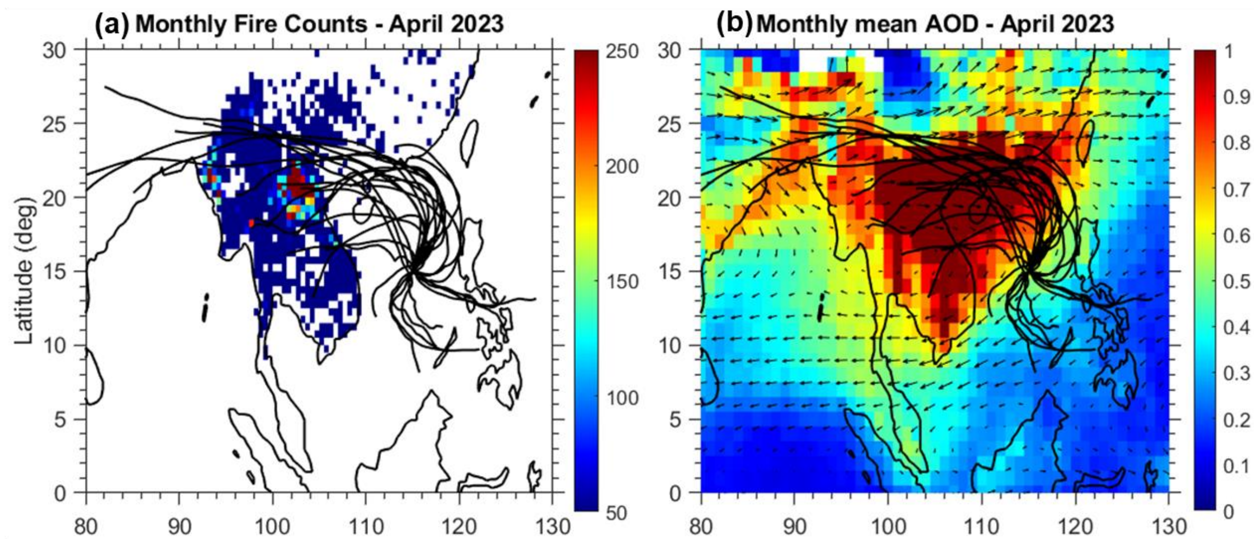

Figure R1. (a) Daily 72-h NOAA HYSPLIT backward trajectories ending at 12:00 UTC at a representative location (15°N, 115°E) over the South China Sea at 3 km altitude, overlaid on MODIS fire counts for April 2023. (b) Same as (a), but overlaid on the monthly mean MODIS aerosol optical depth (AOD) for April 2023.

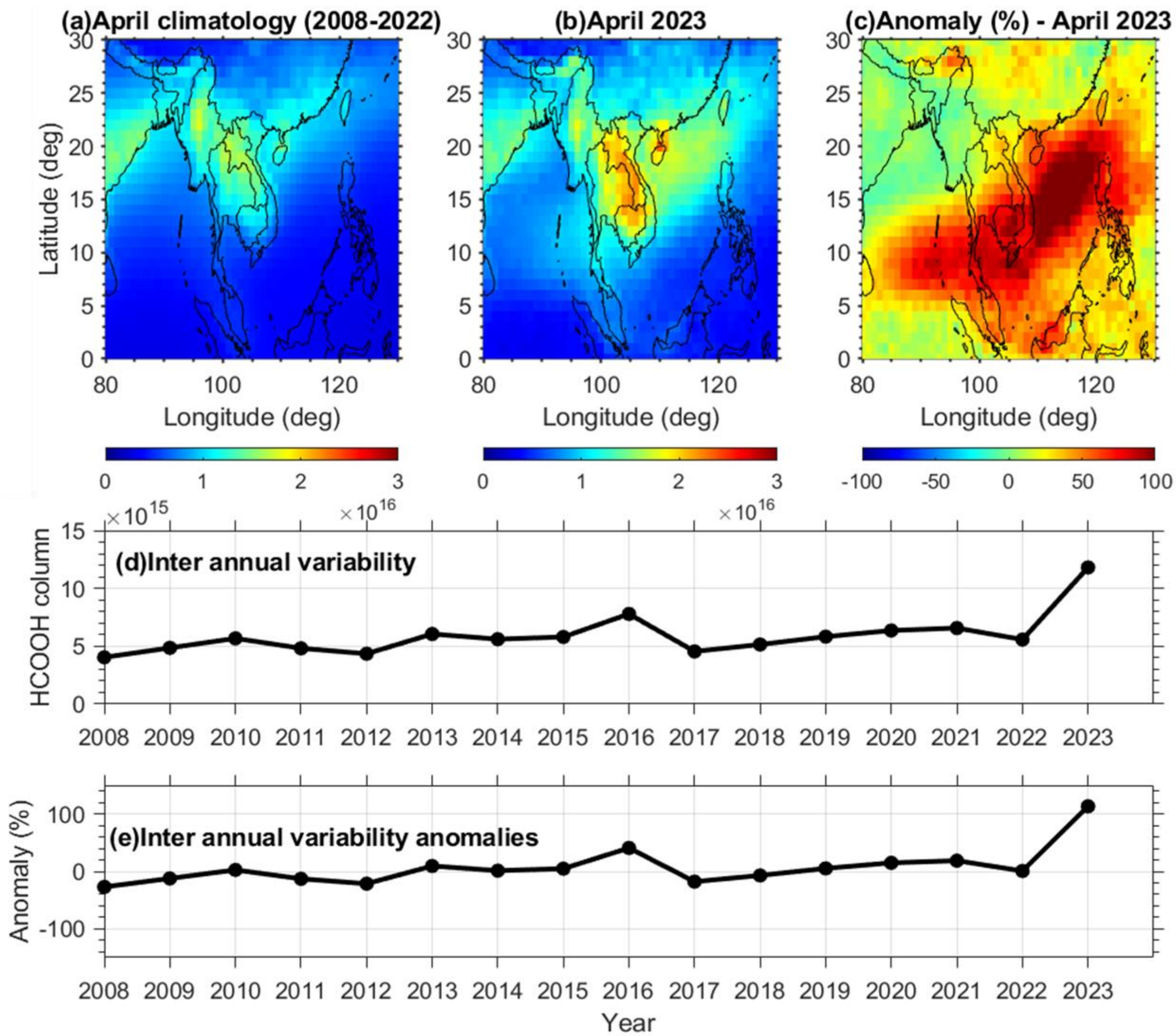

Figure R2. The Infrared Atmospheric Sounding Interferometer (IASI) METOP satellite observed total column HCOOH (a) April long-term mean (2008-2022), (b) April 2023, (c) the percentage change in HCOOH in April 2023 compared to the long-term mean (2008-2022). (d) inter-annual variability of HCOOH in April, and (e) the observed percentage change anomaly in HCOOH over the South China Sea.

Methodology Too Simplistic

The methodology is limited to anomaly calculations relative to the 2003–2022 climatology and σ-thresholds. No advanced statistical diagnostics (EOF, regression, composite analysis) or modeling tools (WRF-Chem, GEOS-Chem, HYSPLIT) are applied. For a high-impact journal, such purely descriptive methods are insufficient. More mechanistic or quantitative approaches are expected to justify publication.

Reply: We appreciate the reviewer's comment. Calculating anomalies relative to a long-term climatological period (2003–2022 in our case) is a well-established and widely accepted method in atmospheric and climate sciences (Avery et al., 2017; Hirsch and Koren, 2021; Hedelius et al., 2021; Rieger et al., 2021; Stone et al., 2025; Prasanth et al., 2025). Comparing these anomalies with the corresponding monthly standard deviations provides a quantitative measure of their extremity. In our study, we clearly state that the observed AOD anomaly in April 2023 exceeded the long-term mean by more than four standard deviations, indicating an exceptionally event. It is also noted that similarly focused studies have successfully employed such methods. For example, Hirsch and Koren (2021), in their *Science* article ("Record-breaking aerosol levels explained by smoke injection into the stratosphere"), used fundamental anomaly analysis to identify record-high AOD levels resulting from the Australian wildfires (See the attached figure below). This highlights that the suitability of methodology depends on the study objective, and complex statistical techniques are not always required for publication in high-impact journals.

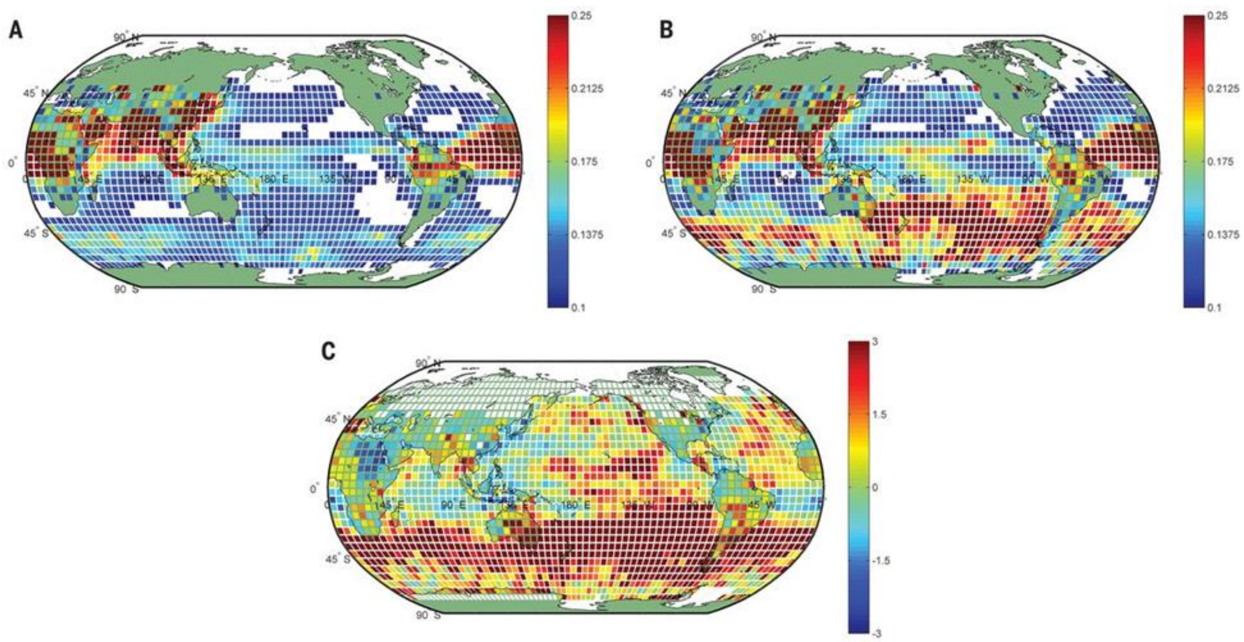

Fig. 2 The SH anomaly for January 2020 (spatial resolution of 5° by 5°).

(**A**) Interannual (2003 to 2019) monthly average AOD values for January. (**B**) Monthly AOD values for January 2020. A notable increase in the AOD values over the SH is observed. (**C**) The change in January 2020 AOD values compared with the interannual January average (expressed in standard deviation units). (source: Hirsch and Koren, 2021, *Science*.)

However, we fully agree with the reviewer that approaches such as EOF analysis, regression, and chemical transport modeling (e.g., WRF-Chem, GEOS-Chem) are highly valuable for exploring underlying mechanisms and causal relationships. Following the reviewer's helpful suggestion, we have included HYSPLIT backward trajectory analysis in the revised manuscript to provide additional evidence for long-range transport from biomass-burning regions (see Figure R1). We also examined AOD variability across the study region using EOF analysis; the results are shown in the attached figure (Figure R3) for your reference. An EOF analysis was applied to the observed monthly mean AOD time series in the study region (90-120E, 5-25N) to determine the dominant modes of variability over the period. The spatial distribution and temporal amplitude are negative, resulting in a positive value. A higher negative value indicates higher AOD. Figure 2(a) shows higher AOD in the northern PSEA and the coastal area of southern China. The result of EOF1 * PC1 (multiplication) is the same.

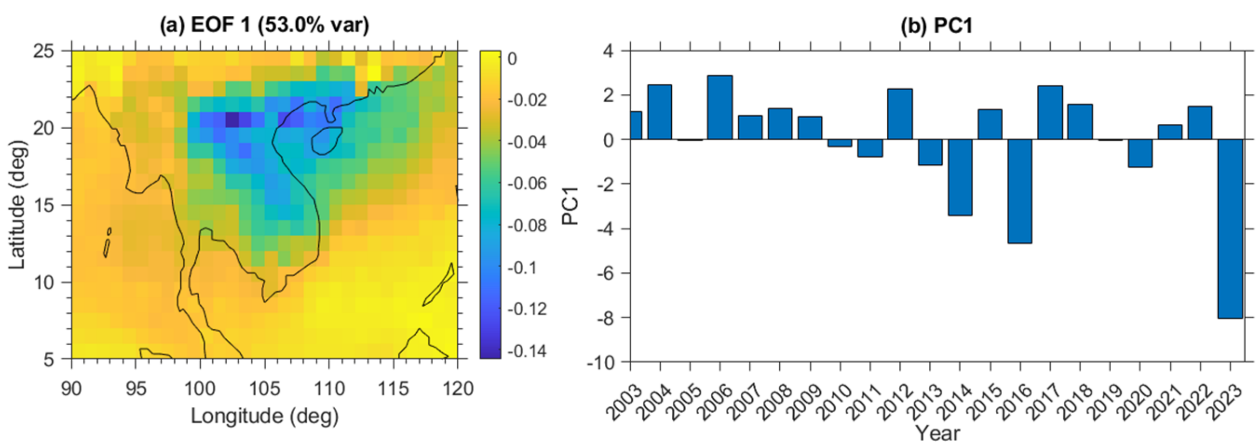

Figure R3. (a) The spatial distribution, and (b) its corresponding time-varying amplitude for the vector EOF analysis mode 1 of the April AOD in SCS during 2003 to 2023.

We agree that chemical transport models such as WRF-Chem and GEOS-Chem could provide further insight into the chemical and physical processes involved. However, incorporating such models is beyond the scope of this observational and event-focused study. We will clearly state this limitation in the revised manuscript and consider it a priority for future research.

Logical Flow and Structure

The introduction devotes excessive space to global wildfire events (Canada, Hawaii, Mediterranean), which dilutes the focus on the SCS case.

Reply: Thank you for your insightful comment. The discussion of global wildfire events (e.g., in Canada, Hawaii, and the Mediterranean) was included in the introduction to highlight the unusually active and widespread nature of wildfires during the study period, placing the South China Sea (SCS) event within a broader global context. However, we understand that this may have diluted the focus on the SCS case. In response, we have revised the introduction to briefly summarize the global activity while more clearly emphasizing the relevance and distinctiveness of the SCS aerosol episode, ensuring that the central focus of the study remains clear.

The Results and Discussion section frequently shifts between AOD, CO, fire counts, meteorology, circulation, and ozone, without a clear hierarchical structure. This leads to a confusing narrative.

The manuscript would benefit from a re-organization: Phenomenon confirmation → Source attribution → Circulation mechanisms → Chemical/ozone impacts → Implications.

Reply: Thanks for the voluble suggestion. We have reorganized the results and discussion section in the revised manuscript as suggested by the reviewer.

Data Classification and Transparency

- Satellite products (MODIS, MOPITT, AIRS, OMI/MLS), reanalysis datasets (MERRA-2, GLDAS, GPCP), and in-situ measurements (AERONET, ozonesondes) are all mixed together in one section.
- It is difficult for the reader to distinguish between direct observations, model-assimilated reanalysis, and ground truth data.
- The Data and Methodology section should be reorganized into clear categories: (1) Satellite remote sensing, (2) Reanalysis/model products, (3) Ground-based observations.

Reply: Thanks for the voluble suggestion. We have modified the Data and Methodology section in the revised manuscript as suggested. We also included a table describing the data used in the present study.

Table R1. Details of various data products used in the present study.

Data	Resolution	Source
Aerosol Optical Depth (AOD)	1° × 1°	Aqua and Terra satellite/MODIS
Carbon Monoxide (CO)	1° × 1°	MOPITT and AIRS
Tropospheric Column Ozone (TCO)	1° × 1°	OMI/MLS
Burned Area (BA)	500 m	Aqua and Terra satellite/MODIS
MODIS Collection 6.1 Fire Anomalies		combined Terra and Aqua satellite/MODIS
Wind and Geopotential Height	0.5° × 0.625°	MERRA reanalysis

Use of Supplementary Figures

Key evidence (e.g., climatological AOD distributions, long-term time series) is presented only in Supplementary Figures. Essential results should be in the main text, with Supplementary reserved for additional details or robustness checks. As written, the paper is not self-contained.

Reply: We appreciate the reviewer's valuable comment. We agree that the climatological AOD distributions and long-term time series provide essential context. As suggested by the reviewer, we have moved the key figures showing the climatological AOD distributions and the long-term AOD time series from the Supplementary Materials to the main text (now Figures 2 and 3, respectively).

Map Presentation and Political Sensitivity

Several figures show solid boundary lines in regions with disputed territories (e.g., South China Sea). International journals require disputed boundaries to be indicated with dashed lines and/or with a neutral disclaimer in the captions. The authors must revise all maps accordingly to comply with cartographic and editorial standards.

Reply: We appreciate the reviewer's careful observation and constructive comment. Following the recommendation, we have revised all maps to comply with editorial standards.

Lack of Impact Assessment

The study stops at describing anomalies. There is no evaluation of downstream consequences (e.g., impacts on regional air quality, radiative forcing, health risks). Without such discussion, the significance of the findings remains limited.

Reply: Thank you for your comment. The primary objective of this study is to identify the drivers and underlying physical mechanisms responsible for the record-breaking aerosol loading over the South China Sea. To provide some insight into potential impacts, we focused specifically on associated ozone changes in the present paper. A more comprehensive evaluation of the effects on radiative forcing, atmospheric processes, and air quality is beyond the scope of this study. It will be addressed in a follow-up study.

Minor Comments

Figures are overcrowded, with small fonts and inconsistent styles (gradient colors vs. hatching). Improve readability and adopt a uniform design.

Reply: We have taken utmost care in the figures in the revised manuscript.

Figure 8 schematic is overly simplistic compared to the complexity of earlier figures; it should more clearly contrast climatological vs. 2023 circulation states.

Reply:

Reference formatting is inconsistent; some entries are incomplete or lack DOI.

Reply: Corrected in the revised manuscript

The writing style is verbose. The introduction should be shortened and sharpened to highlight the scientific problem.

Reply: Corrected in the revised manuscript

The format are not clearly uniform between $1\circ \times 1\circ$ in L116 and 0.25° in L124. The font format of L124-125 is different from other context.

Reply: Corrected in the revised manuscript

L140, why the skin temperature is used in this work?

Reply: It is a typo mistake. We used the surface temperature from the AIRS satellite. We have corrected this typo in the revised manuscript.

L187, L198, add ° for the logitude and latitude.

Reply: Corrected in the revised manuscript

L185, Sup. Figures, L188, Sup—Figures, P201, Sup. Fig. and so on, keep the same citaiton style, refer to the papers in the top journals.

Reply: Corrected in the revised manuscript

L 241, the maps are not correct, as we know, there are still undecided boarders between China and India, the author should clearly state them in the maps.

Reply: Corrected in the revised manuscript

References

Hirsch, E. and Koren, I.: Record-breaking aerosol levels explained by smoke injection into the stratosphere, Science, 371, 1269–1274, https://doi.org/10.1126/science.abe1415, 2021.

Avery, M., Davis, S., Rosenlof, K. et al. Large anomalies in lower stratospheric water vapour and ice during the 2015–2016 El Niño. Nature Geosci 10, 405–409 (2017). https://doi.org/10.1038/ngeo2961

Hedelius, J. K., Toon, G. C., Buchholz, R. R., Iraci, L. T., Podolske, J. R., Roehl, C. M., Wennberg, P. O., Worden, H. M., and Wunch, D.: Regional and urban column CO trends and anomalies as observed by MOPITT over 16 years, J. Geophys. Res.-Atmos., 126, e2020JD033967, https://doi.org/10.1029/2020JD033967, 2021.

Rieger, L. A., Randel, W. J., Bourassa, A. E., and Solomon, S.: Stratospheric Temperature and Ozone Anomalies Associated With the 2020 Australian New Year Fires, Geophys. Res. Lett., 48, e2021GL095898, https://doi.org/10.1029/2021GL095898, 2021.

Stone, K., Solomon, S., Yu, P., Murphy, D. M., Kinnison, D., and Guan, J.: Two-years of stratospheric chemistry perturbations from the 2019–2020 Australian wildfire smoke, Atmos. Chem. Phys., 25, 7683–7697, https://doi.org/10.5194/acp-25-7683-2025, 2025.

Prasanth, S., Anand, N. S., Sunilkumar, K., Jose, S., Arun, K., Satheesh, S. K., and Moorthy, K. K.: Australian bushfire emissions result in enhanced polar stratospheric clouds, Atmos. Chem. Phys., 25, 7161–7186, https://doi.org/10.5194/acp-25-7161-2025, 2025.

We once again thank the reviewer for carefully reviewing the manuscript and for offering potential solutions that helped us significantly improve its content.